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Consistent MMI area estimation for Australian earthquakes

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ABSTRACT: Over the last three decades several Modified Mercalli Intensity (MMI) predicative equations have been developed for Australia. These have all been for a specific MMI level, typically MMI III. Using newly available MMI point data and adopting international practices, this paper proposed a new Intensity Prediction Equation for Australia that uses a single equation to predict the MMI for earthquakes in the range Mw 2.0 to 7.0 and at distances from 1 to 1000 km. We demonstrate that the combination of one PGA-to-MMI relations with the weighted average of three GMPEs, accurately replicates the proposed IPE. This enables consistent forecasting of MMI regions whether directly from an IPE or scenario modelling using seismic hazard and/or risk software.

1 INTRODUCTION

1.1 **A level 2 heading**

Geoscience Australia (GA) has been providing estimates of felt and potential damage radii for all earthquakes above magnitude 3.5, since 2002. Similarly, over the last decade, using the hazard modelling software EQRM, GA has produced scenario Modified Mercalli Intensity (MMI) maps for most Australian cities, and several cities in our region. The former uses empirical relations developed from measuring the radii of MMI levels III, IV, V and VI from the isoseismal map of ~100 Australian earthquakes. The latter uses various ground motion prediction equations (GMPEs) to generate the hazard field, then PGA / PGV to MMI conversions to estimate MMI. This study compares several empirical Intensity Prediction Equations (IPE) and proposes a preferred IPE for Australia. It then investigates what combination of GMPE and PGA-to-MMI conversion best fits the preferred IPE.

2 PREVIOUS WORK AND DATA

Several relations for estimating the MMI area of Australian earthquakes have been developed (McCue 1980, Michael-Leiba 1989, Greenhalgh 1989, Burbidge 2002(pers comm), Burbidge 2007 [in Dent *et al.* 2007]). Most of these relations have the form $R_X = a_X * b_X^{ML}$, where X is the isoseismal level of interest, R_X is the radius of isoseismal level X, ML is the magnitude and a_X & b_X are the constants estimated. These relations tend to have large uncertainties with 2σ typically being a factor of two. For example, R_{III} for a 5.0 ML earthquake might be 100 km, with a 2σ range of 50 - 200 km. Given this high uncertainty, all the relations give statistically indistinguishable results above ML 3.4. In this study we employed the approach used by Burbidge (2002), who took the average of the maximum and minimum epicentral distance of the contours to calculate the average for a given MMI. We measured the maximum and minimum diameter of the larger earthquakes and used these data to slightly modify the Burbidge 2007 relations to achieve a better fit to the data from these larger earthquakes. Table 1 presents the a_X and b_X coefficients for the Michael-Leiba (1989), Burbidge (2002, 2007) and this study.

Table 1 Intensity Prediction Equations developed for Australia

MMI	This Study		Burbidge (2002)		Burbidge (2007)		McCue (1980)		Michael-Leiba (1989)	
R = a x b^{ML}	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
III	1.58	2.5	1.3	2.58	1.9	2.38	0.88	2.69		
IV	2.03	2.3	0.62	2.73	0.9	2.57			0.86	2.57

V	1.04	2.21	0.47	2.48	0.4	2.50				
VI	0.051	3.2	0.05	3.178	0.048	3.26				

Internationally, there have been several IPEs developed in recent years. Dowrick and Rhoades (2005) developed one for New Zealand, Atkinson and Wald (2007) for Western U.S. and Central and Eastern U.S., Sørensen *et al.* (2009) for Northwest Turkey, and Allen *et al.* 2012 for global active crustal regions. There are large differences between these relations, with for example the Atkinson and Wald (2007) eastern U.S radius being 300-400% greater than the western U.S. radius. This is attributable to the low attenuation cratonic crust of the eastern U.S. These IPEs differ from the Australian ones in that, in the case of the former, a single equation allows the MMI to be estimated from the earthquake magnitude and distance, whereas the Australian IPEs use a separate equation for each MMI of interest and, due to the lack of empirical data, have only been calculated for a limited subset of MMI, typically MMI III – V.

3 INTENSITY PREDICTION EQUATIONS FOR AUSTRALIA

Allen *et al.* (2012) developed an IPE for global continental crust (Equation 1 and Table 2). Australian MMI point data for Mw ≥ 5.5 (per Allen *et al.* 2012) is available for six earthquakes, the 1968 Mw 6.5 Meckering, 1988 Mw 6.6 and 6.2 Tennant Creek, 1979 Mw 6.1 Cadoux, 1970 Mw 5.5 Calingiri and 1989 Mw 5.4 Newcastle earthquakes. Visually comparing the Allen *et al.* 2012 IPE to MMI digital data for these six earthquakes (Figure 1) suggests that the relation underestimates the radius/MMI for Australian data. We visually refitted the Allen *et al.* (2012) IPE to the Australian data, resulting in an IPE that gives about a 66% larger radius than the original. The Allen *et al.* (2012) IPE has a 1σ uncertainty of a factor of 2 in distance and ±1 MMI units. Given these uncertainties and the differences between the various IPE, we consider an increase by 66% reasonable. The functional form of the equation is:

$$MMI = C_0 + C_1 * Mw + C_2 * \ln\left(\sqrt{R^2 + (1 + C_3 * exp(Mw - 5))^2}\right) \qquad 1$$

where R is is the distance to the fault and C_0, C_1, C_2, and C_3 are the parameters to be fitted. R can be either closest distance to rupture (Rrup) or hypocentral distance (Rhyp) though the parameters are different for the two distance measures.

Table 2 Parameters for the IPE or Allen et al. 2012

Study	Distance	C0	C1	C2	C3
Allen *et al*. 2012	*Rrup*	3.95	0.913	-1.107	0.813
Allen *et al*. 2012 (modified)	*Rrup*	3.5	1.05	-1.09	1.1

The IPEs, including Allen *et al*. (2012), tend to be the mean of the digitised MMI data. Placement of contours on isoseismal maps is always qualitative, but they tend to be organised such that each contour captures almost all instances of its respective MMI level – and so is close to the dividing line between the MMI and the next lower MMI. These distances are usually greater than what would be estimated by an IPE, so to replicate the isoseismal contour radius with an IPE, a MMI 0.5 units lower should be used in the IPE (e.g. the IPE MMI 2.5 distance will approximate a MMI 3.0 isoseismal map radius). As noted by Hough *et al*. (2000) care needs to be taken to ensure the method by which an IPE has been estimated is taken into account when applying that IPE.

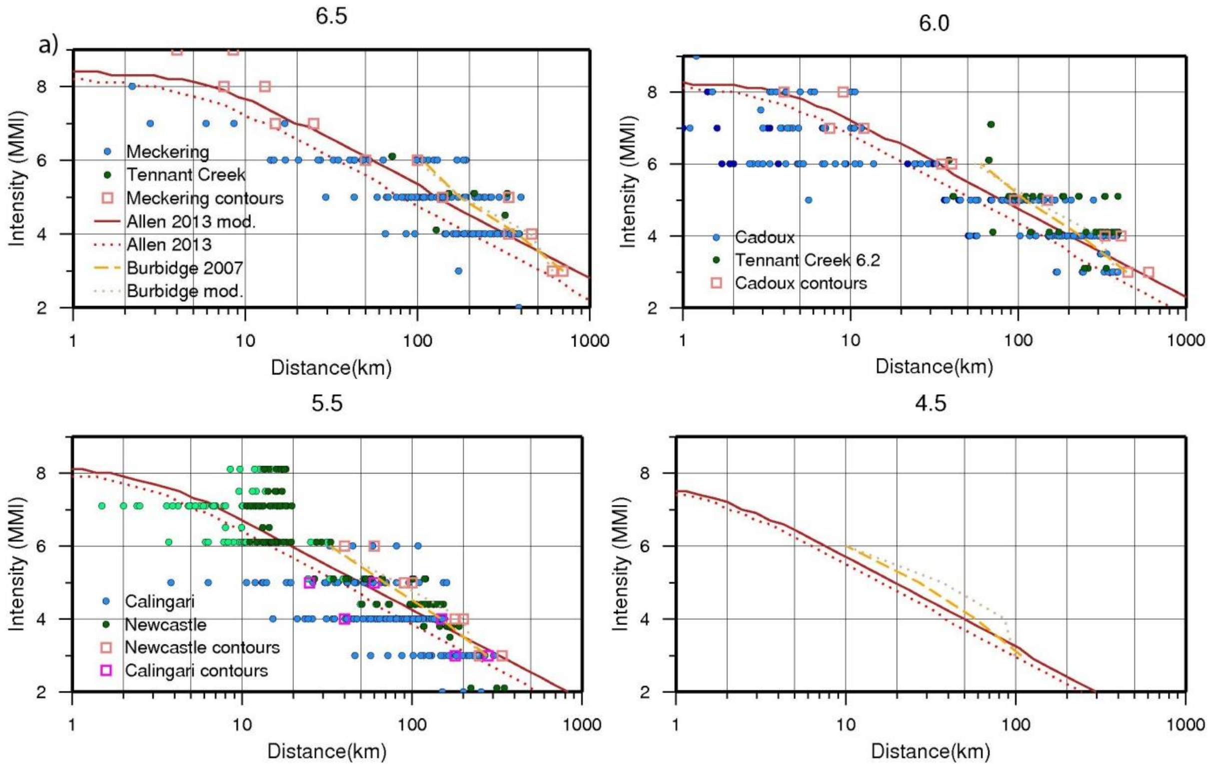
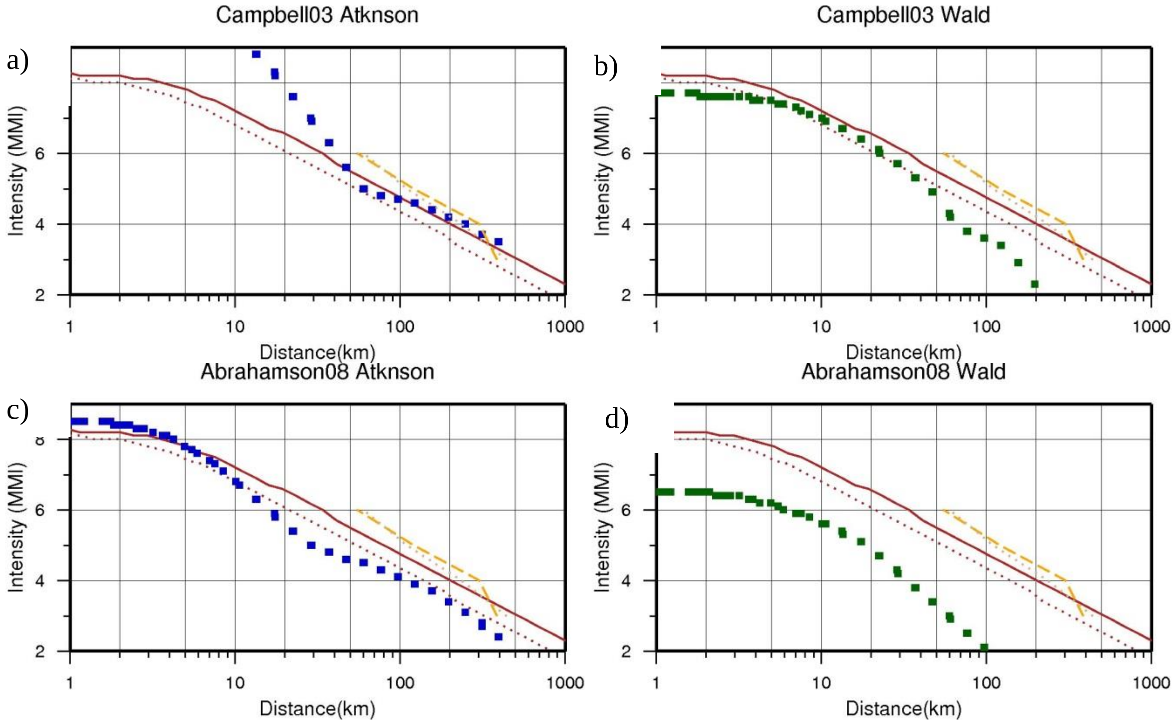


Figure 1Comparison of IPEs and digital MMI data for the larger earthquakes, for M 6.5 (a), 6.0 (b), 5.5 (c) and 4.5 (d).



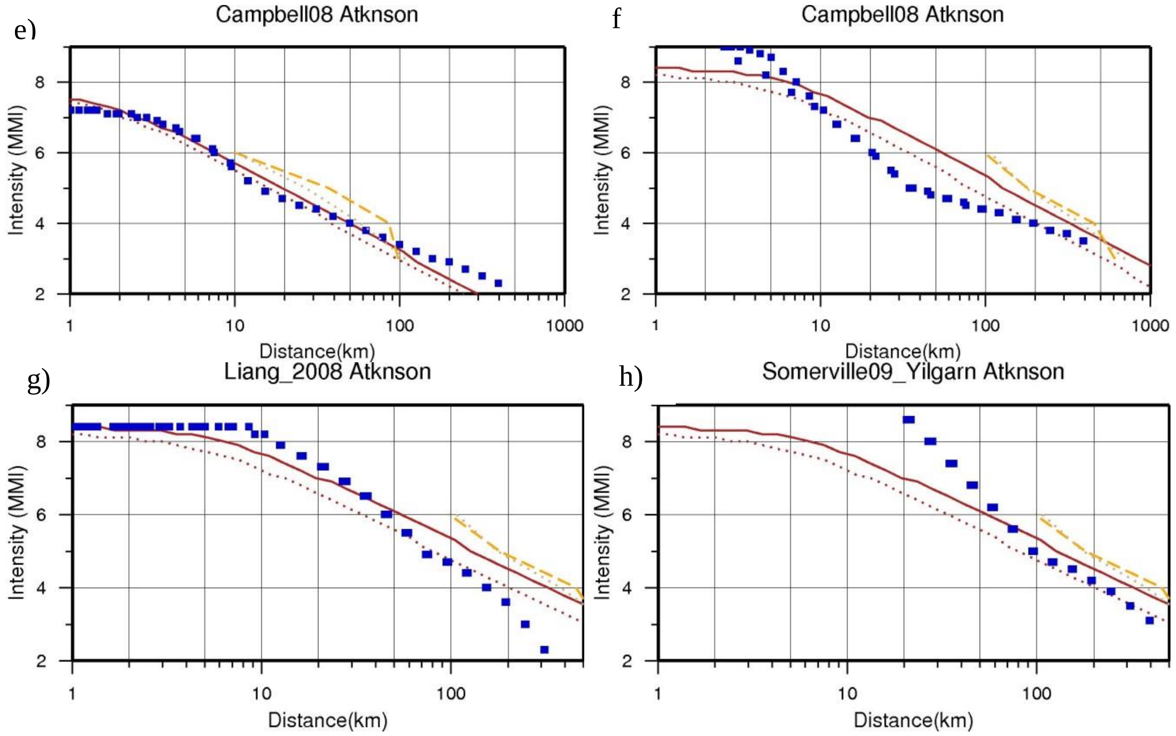


Figure 2 Variations between different GMPEs and PGA to MMI conversions. The lines are as for Figure 1 and the blue squares are the results of the earthquake scenario. (a) & (b) and (c) & (d) compare two GMPEs with two PGA to MMI conversions for Mw = 6.0. (e) & (f) use the same GMPEs and PGA to MMI conversion but to magnitudes (4.5 & 6.5). (g) & (h) are both Mw = 6.5 and use the same PGA to MMI conversion but use different GMPEs.

4 BEST FIT GMPES COMBINED WITH PGA TO MMI CONVERSIONS

We calculated the expected PGA from four shallow earthquakes (Mw 4.5, 5.5, 6.0, and 6.5) using 25 different GMPEs, for V_{S30} of 760 m/s, and two PGA to MMI conversions Atkinson and Kaka (2007) and Wald *et al*. (1999). The Worden *et al*. (2012) relation was also considered, but as it is intermediate between those used it is not further considered here. The recently published Caprio *et al*. (2015) relation is similar to the Atkinson and Kaka (2007) and is not further considered here. The faults of the scenario earthquakes have a strike of 0° and a dip of 45°. The depths were all shallow ranging from 0.8 km for the Mw 4.5 to 3.5 km for the Mw 6.5. The sites were logarithmically spaced along a line with an azimuth of 90° running through the epicentre. The data was then plotted using Rrup. We then visually assessed the fit of the scenario MMIs to the Australian MMI observations. Figure 2 shows eight of the scenarios.

No single combination was found to be a good fit to the data over the full magnitude and distance ranges. Atkinson and Kaka (2007) consistently fit the Australian MMI relations better than the Wald *et al*. 1999 (Fig. 2 a & b and c & d).The exceptions being when the Wald *et al*. (1999) relation was paired with a low attenuation Cratonic GMPE such as Campbell (2003) or Somerville *et al*. (2009)(Yilgan). Relations that were a good fit at Mw 4.5 were often a poor fit at Mw 6.5 (Fig. 2 e vs. f). The NGA08-west relations tended to underestimate the MMI at larger distances and low MMI (Fig. 2 g). Stable continental relations tended to overestimate MMI at close distances (e.g. Fig. 2 h).

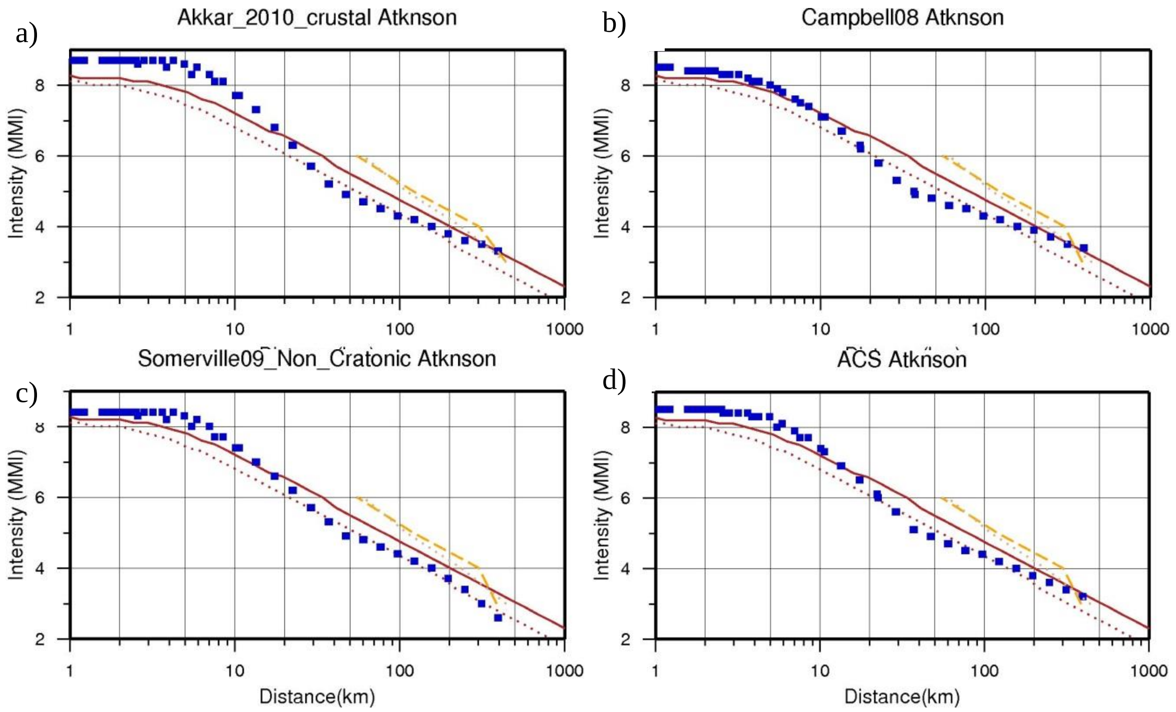


Figure 3 The three trial GMPEs and the preferred weighting of the three, combined with Atkinson and Kaka (200) relation for Mw 6.0

In combination with the Atkinson and Kaka (2007) relation, the GMPEs of Akkar and Bommer (2010), Campbell and Bozorgnia (2008) and Somerville *et al*. non-cratonic (2009) all give a reasonable fit to the data (Fig. 3). Figure 3(d) presents the results of combining Atkinson and Kaka (2007) with the weighted average of these three GMPEs (with weights of 0.2, 0.4 and 0.4, respectively). Figures 4, 5 and 6 show these same four combinations, for Mw 4.5, 5.5 and 6.5 earthquakes. The weighted average compares favourably across the range of magnitudes – though, for a specific magnitude, a single GMPE can give a better fit (e.g. Campbell *et al*. (2008) for Mw4.5).

For Mw above 6.0 the fault length can become larger than *Rrup*. In these cases the IPE relation should no longer be used to estimate the radius of a circle centred on the epicentre. Using the relation log(L) = 0.6 Mw – 2.59 (Leonard 2014), stable continental crust earthquakes of Mw 6.0, 6.5 and 7.0 will have fault lengths of 10, 20 and 41 km respectively. For a Mw 6.5 the *Rrup* for MMI 8 is 6.0km, when applying the modified parameters presented in Table 2. This gives an area of 353 km^2,which is equivalent to a circle with a radius of 10.7 km. Equation 1 rearranged to give *Rrup* is given in Equation 2, and the equivalent distance to epicentre, *Repi*, is given in Equation 3.

$$Rrup^2 = \left(\exp\left(\frac{MMI - C_0 - C_1 * Mw}{C_2}\right)\right)^2 - (1 + C_3 * exp(Mw - 5))^2 \qquad 2$$

$$Repi = \sqrt{\frac{(\pi Rrup^2 + 2\, Rrup\ 10^{(0.6\,Mw - 2.59)})}{\pi}} \qquad 3$$

Table 3 gives *Rrup* and *Repi* for a range of MMI and Mw. From this it is clear that for larger earthquakes (i.e. Mw > 6.0) and higher intensity (i.e. MMI ≥ VIII) *Rrup* and *Repi* should not be used interchangeably.

Table 3 Distance to rupture (Rrup) and distance to epicentre (Repi) for a range of Mw and MMI.

		Mw									
MMI		2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
Fault Length (km)		0.14	0.25	0.45	0.8	1.4	2.6	5.1	10.	20.	41
Rrup (km)	3	17.5	28.4	46.1	74.6	120.7	195.4	316.3	512.1	828.9	1341.9
	4	6.9	11.3	18.4	29.8	48.2	78.1	126.4	204.6	331.2	536.1
	5	2.6	4.4	7.2	11.8	19.2	31.1	50.4	81.7	132.2	214.0
	6	0.3	1.4	2.7	4.5	7.5	12.3	20.0	32.4	52.5	85.1
	7				1.3	2.6	4.5	7.6	12.4	20.3	33.0
	8							1.6	3.4	6.0	10.2
		Mw									
MMI		2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
Repi (km)	3	17.6	28.5	46.2	74.8	121.1	196.2	318.0	515.3	835.4	1354.8
	4	7.0	11.4	18.5	30.0	48.6	78.9	128.0	207.8	337.6	548.9
	5	2.6	4.4	7.4	12.0	19.6	31.9	52.0	84.8	138.5	226.6
	6	0.3	1.5	2.8	4.7	7.9	13.1	21.6	35.5	58.7	97.2
	7				1.5	3.0	5.3	9.0	15.3	26.0	44.1
	8							2.8	5.8	10.7	19.2

5 CONCLUSION

The Allen *et al*. (2012) IPE relation has been tuned to the MMI observations from the six larger Australian earthquakes. As demonstrated in Figures 3, 4, and 5, the combination of the Atkinson and Kaka 2007 PGA-to-MMI relations with the weighted average of the Akkar and Bommer (2012), Campbell and Bozorgnia. (2008) and Somerville *et al*. non-Cratonic (2009) GMPEs, accurately replicates the tuned IPE. This enables consistent forecasting of MMI regions whether directly from an IPE or scenario modelling using seismic hazard and/or risk software.

As the Allen *et al*. (2012) IPE relation, and the tuned version proposed here, were constrained using earthquakes in the magnitude range Mw 5.0 -7.9 and for distances less than 500km, they are only valid within this range. Figure 7 shows the MMI estimated by the proposed relation down to Mw 2.0. The values for MMI III and IV were visually compared to a couple of dozen isoseismal maps for earthquakes with magnitudes between M 2.0 and 4.0. In this qualitative analysis, given the factor of 2 in variability of the distances, the estimated distances were consistent with those observed in the isoseismal maps. This suggests that while the relation is not technically valid below Mw 5.0 in practice they are fit for purpose when used in real-time to provide indicative estimates or felt (MMI III) and minor damage (MMI V & VI) areas.

b)

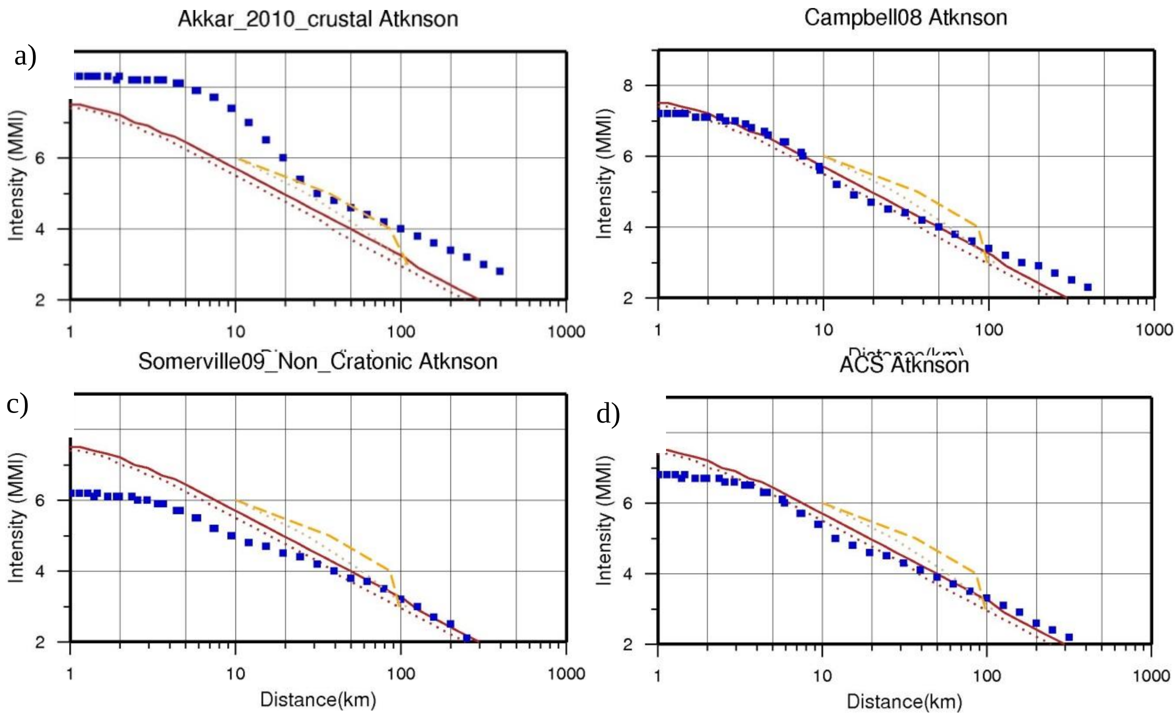


Figure 4 The three trial GMPEs and the preferred weighting of the three, combined with Atkinson and Kaka (200) relation for Mw 4.5

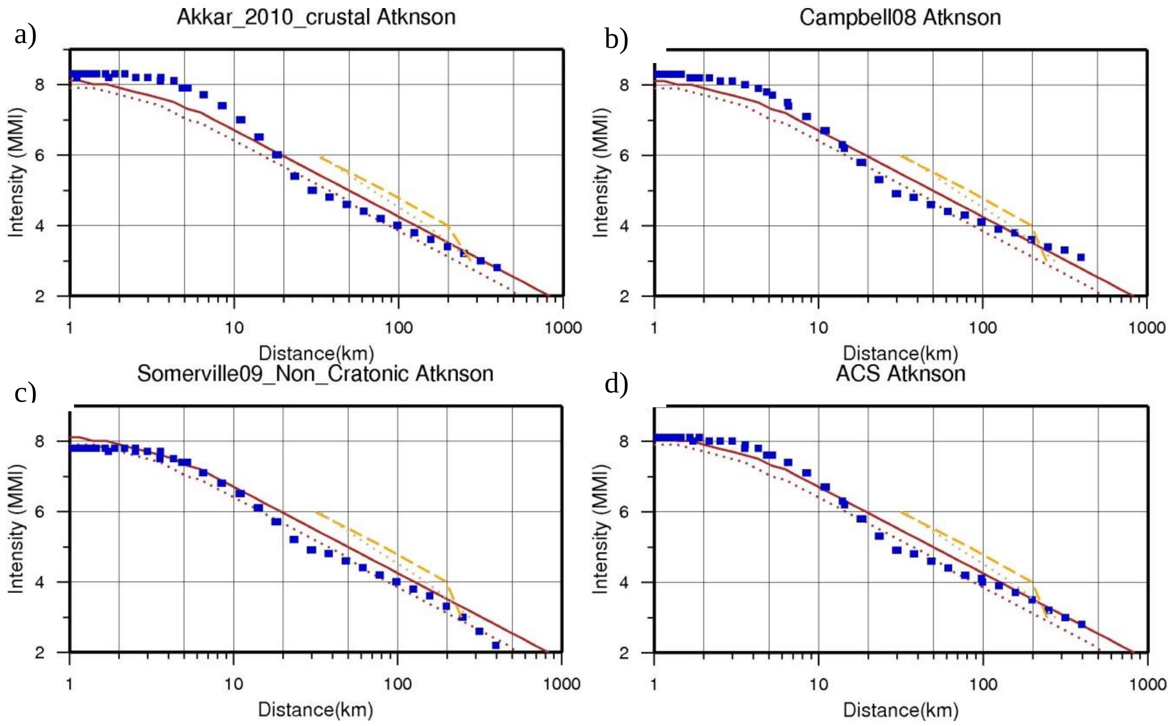


Figure 5 The three trial GMPEs and the preferred weighting of the three, combined with Atkinson and Kaka (200) relation for Mw 5.5

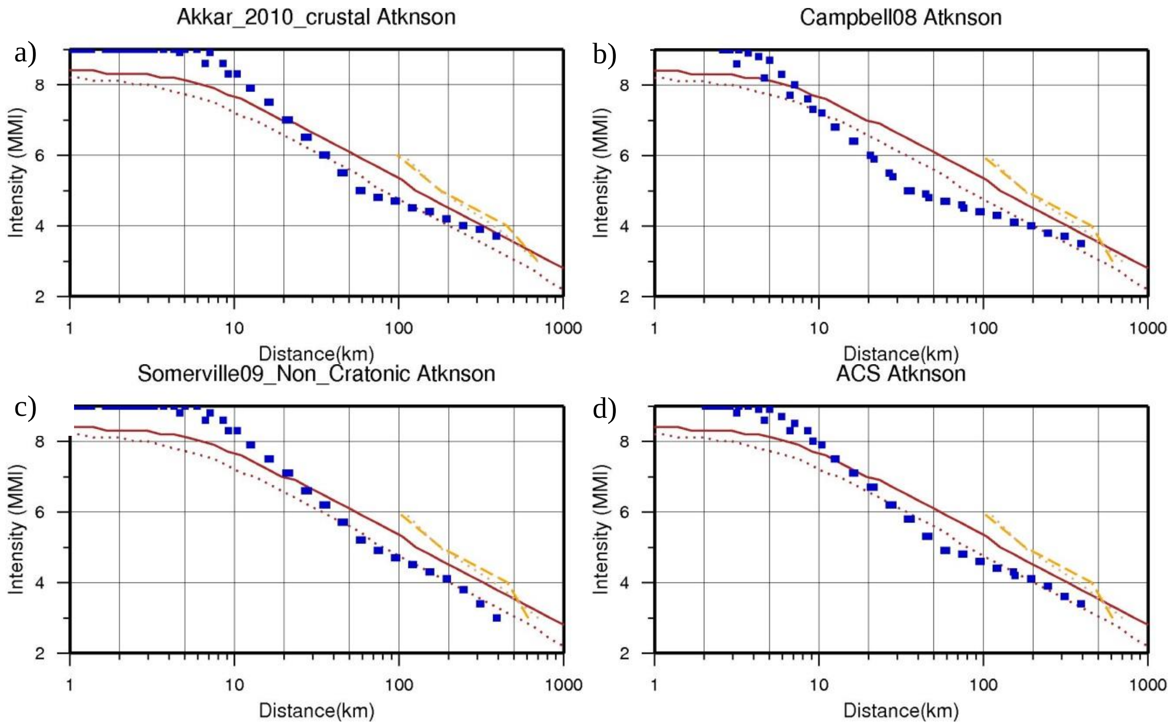


Figure 6 The three trial GMPEs and the preferred weighting of the three, combined with Atkinson and Kaka (200) relation for Mw = 6.5

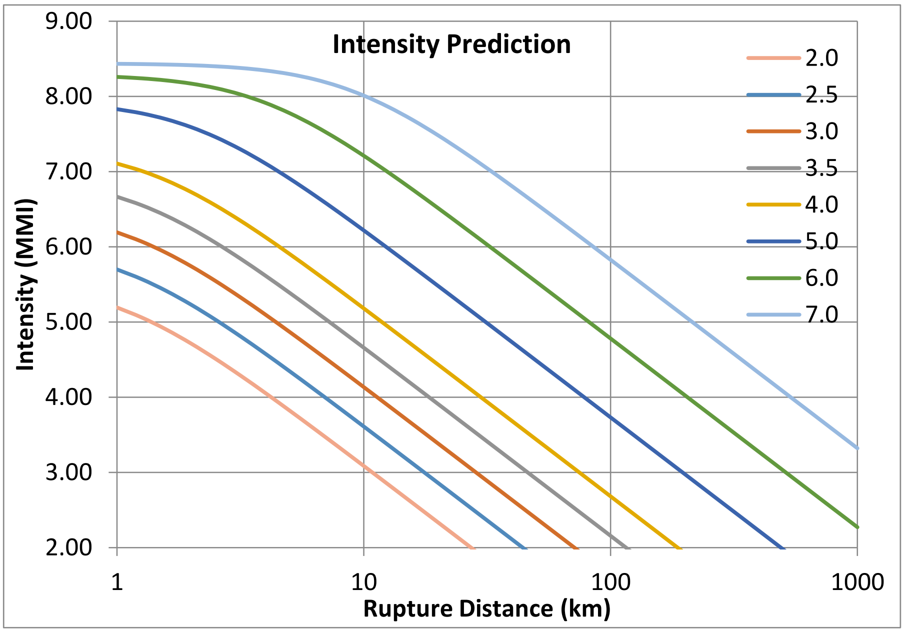


Figure 7 The Intensity predictions using Equation 1 and the constants given in Table 2.

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